Introduction to the analysis of Cherenkov Telescope data

From raw data to shower images

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Outline

- Remainder: What do we see with a CT?
- I. Processing of the pixel signals & Calibration
- II. Extraction of the shower Image & Parameterization
- III. Characterization of the event
  - Incoming direction
  - Gamma or hadron ?
  - Energy estimation

Lo più importante che dovresti avete imparato fino adesso su i telescopi Cherenkov

What at CT sees

- Typical question of visitors to MAGIC site: “with such a big telescope you have to SEE large nice pictures of planets/stars/galaxies”

What at CT sees

- Typical question of visitors to MAGIC site: “with such a big telescope you have to SEE nice pictures of planets/stars/galaxies”

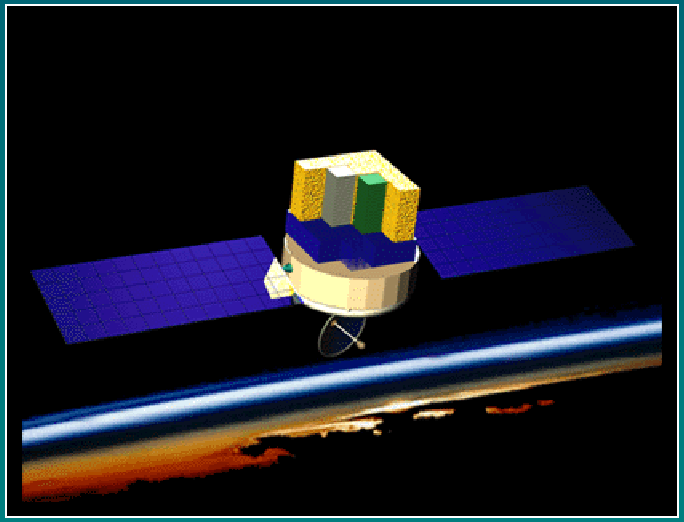
- No, conversely to optical telescopes we do NOT SEE stars. We RECORD NUCLEAR reactions in the atmosphere, in particular the flashes of Cherekov light which accompany them.

Cherenkov Technique

Basic fact: γ-rays absorbed in atmosphere

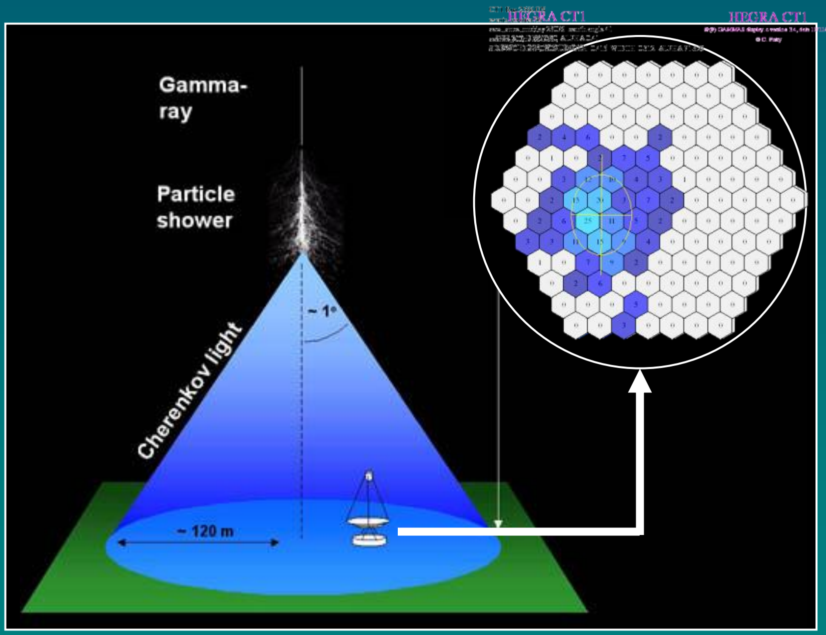
Satellites

- **Direct detection**
- No background
- Small Effective Area ~1m^2



Ground Detectors

- **Indirect detection**
- Huge Effective Area ~ $10^5 m^2$
- Enormous hadronic background

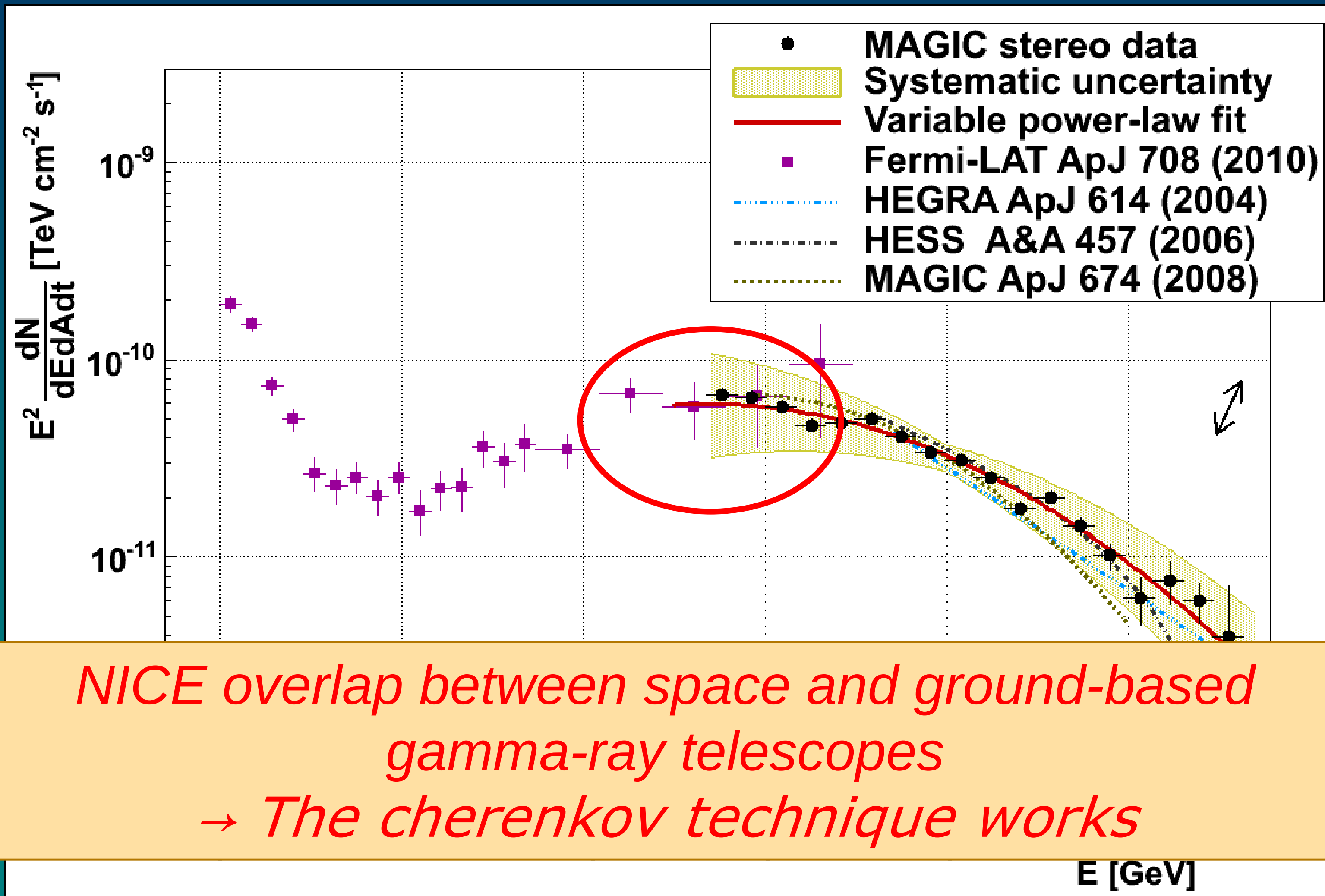


What at CT sees

What at CT sees

- So, we see atmospheric showers.
  - Comparing the number of showers coming from one position of the sky with respect to the bg. we _*sometimes*_ see an excess of events
  - Then we _*assume*_ this excess as Gammas coming from the source
  - And finally we _*infer*_ properties about the source
- The nice thing is that this _*indirect*_ way of doing gamma-ray astronomy works!

What at CT sees

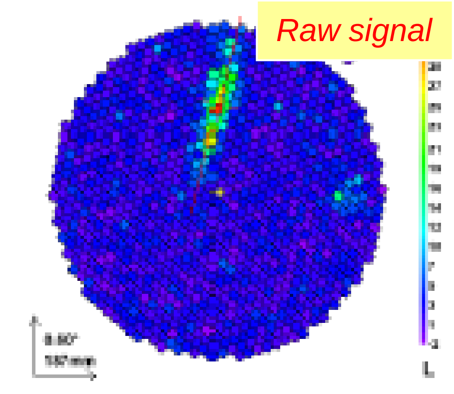


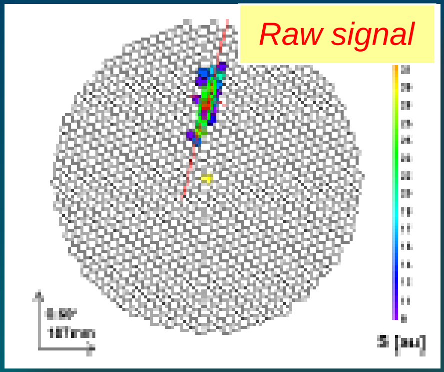
NICE overlap between space and ground-based gamma-ray telescopes
→ The cherenkov technique works

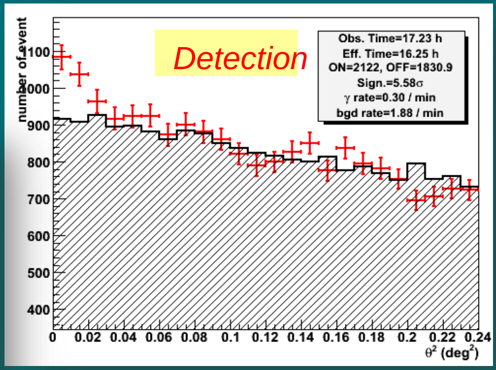
Steps of the Analysis of CT data

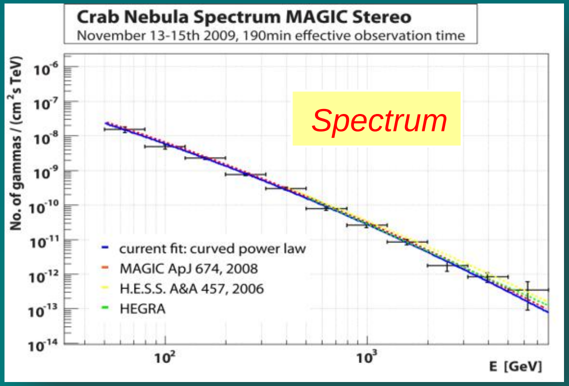
This talk

- Pixel signal extraction
- Image cleaning
- Image parameterization
- Stereo- reconstruction
- Event parameter reconst
- Background rejection
- Background estimation
- Source detection
- Sky maps
- Spectrum / light curve
- Spectrum Unfolding



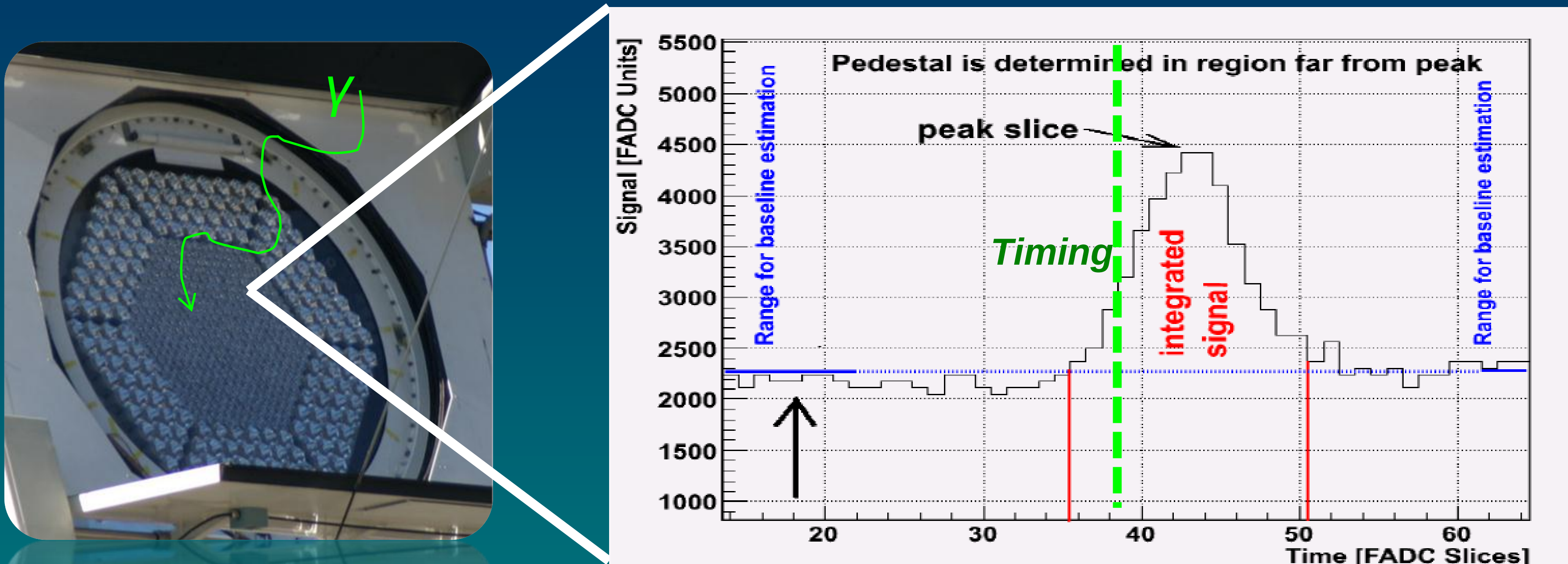






I. Processing pixel signals & Calibration

Pixel signal extraction



- For each pixel we get:
  - integrated charge Q (FADC counts)
  - arrival time T (ns)

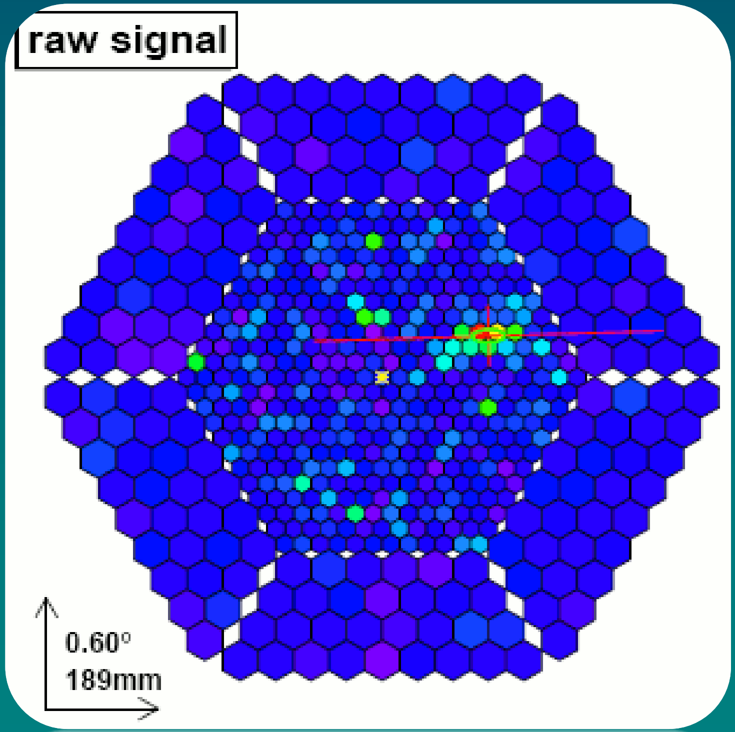
Signal in Photo-electrons

<u>Raw Signal</u> = pedestal + (Cherenkov light) x PDE x gain

Calibration

Pixel signal extraction

- For each pixel we get:
  - integrated charge Q (FADC counts)
  - arrival time T (ns)
- Then we get a raw image of the shower.



Calibration

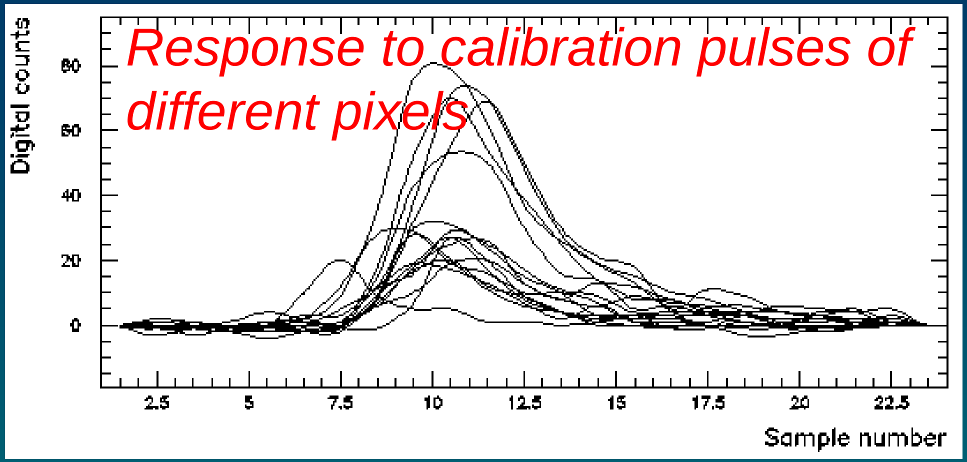
Needed to:

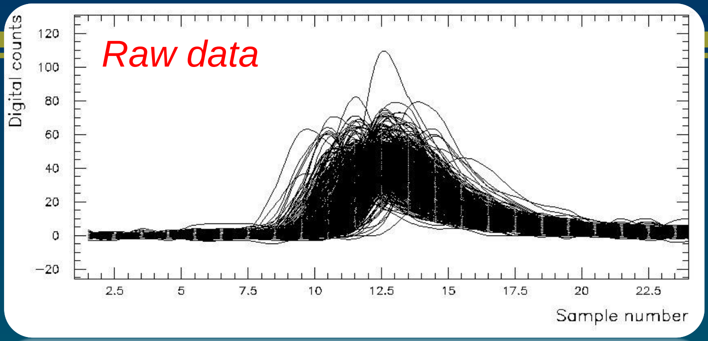
- Convert charges from FADC counts to ph.e. (or photons)
- Correct for the differences between pixels:
  - Different Photo Detection Efficiency & gains -> calibrate Q
  - Different cable lenghts and transit time in pmt's -> calibrete T

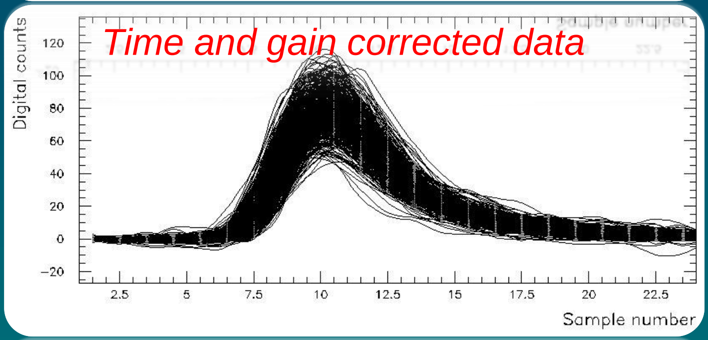
Method:

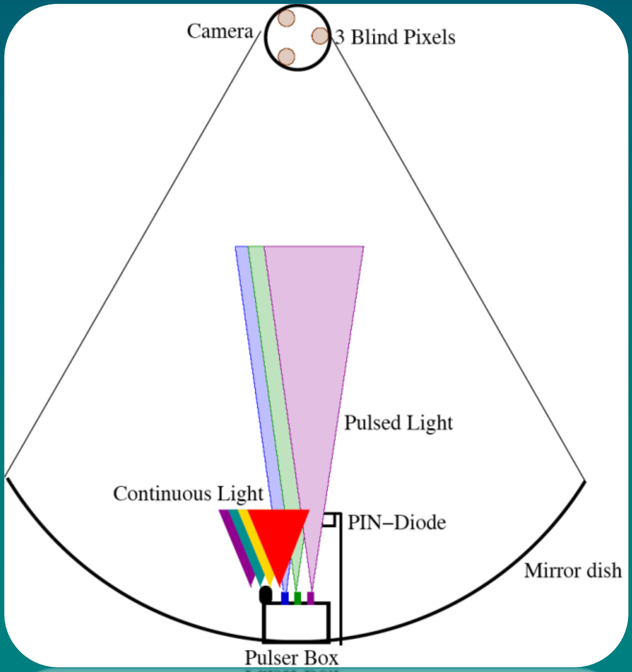
- Take calibration runs. Camara iluminated with Uniform light flashes (Flat fielding)
- Muons signal

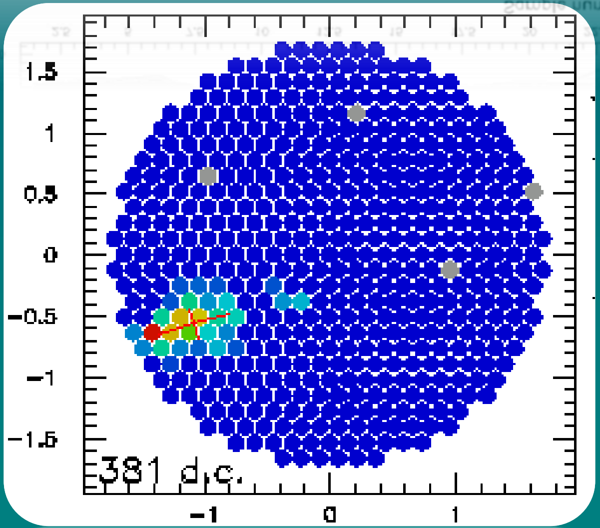
Calibration











II. Extraction of the shower Image & Parameterization

Image Cleaning

Goal: Keep only pixels iluminated by the shower, i.e. remove pixels due to NSB

Depending on the Cleaning Levels more or less pixels survive.

A compromise is needed to retain as many shower pixels as possible but as less as possible NSB pixels

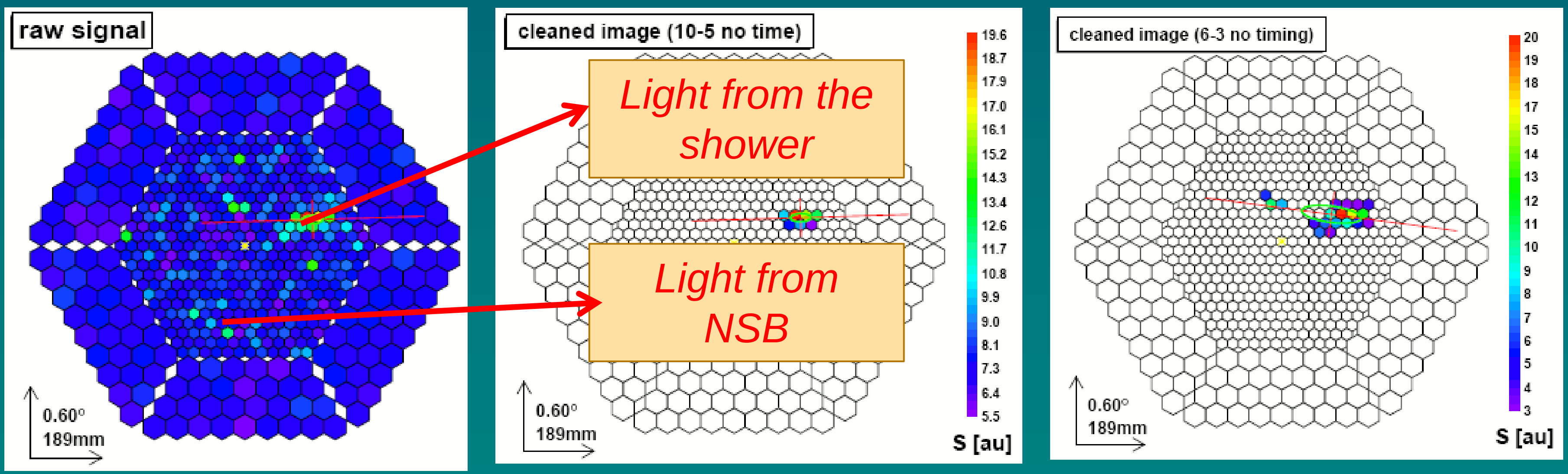
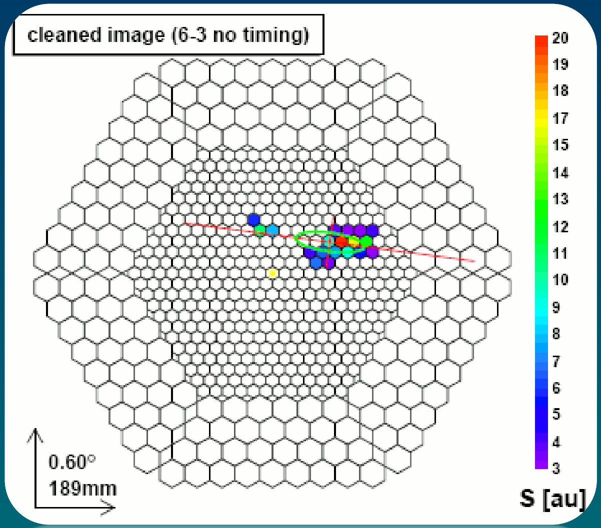


Image Parameterization



Input:

- *List of used pixels (after cleaning)*
- *Signal in each pixel*
- *pulse time of each pixel*

Output

- ***Image quality :*** *Number of Islands, leakage…*
- ***Hillas parameters:*** *Width, Length…*
- ***Extra Hillas parameters:*** *Concentration, asymmetry…*
- ***Source dependent parameters:*** *Disp, alpha...*
- ***Time parameters:*** *time gradient, time RMS…*
- ***Stereo parameters:*** *height of shower max, impact point…*

Hillas parameters

Idea: *Images of gamma showers have an oval shape.*
They can be described by an ellipse, defined by:

- ***Size (or Sum):*** *Σ pixel signal*
- ***Centroid:*** *Coordinate of the center of gravity (x,y)*
- ***Main Axis (δ angle):***
  - Line minimizing signal-weighed sum of squared pixel distance.
  - Angle of the 2nd moment matrix diagonalization.
- ***Length:*** *Signal RMS along main axis*
- ***Width:*** *Signal RMS perpendicular to the main axis*

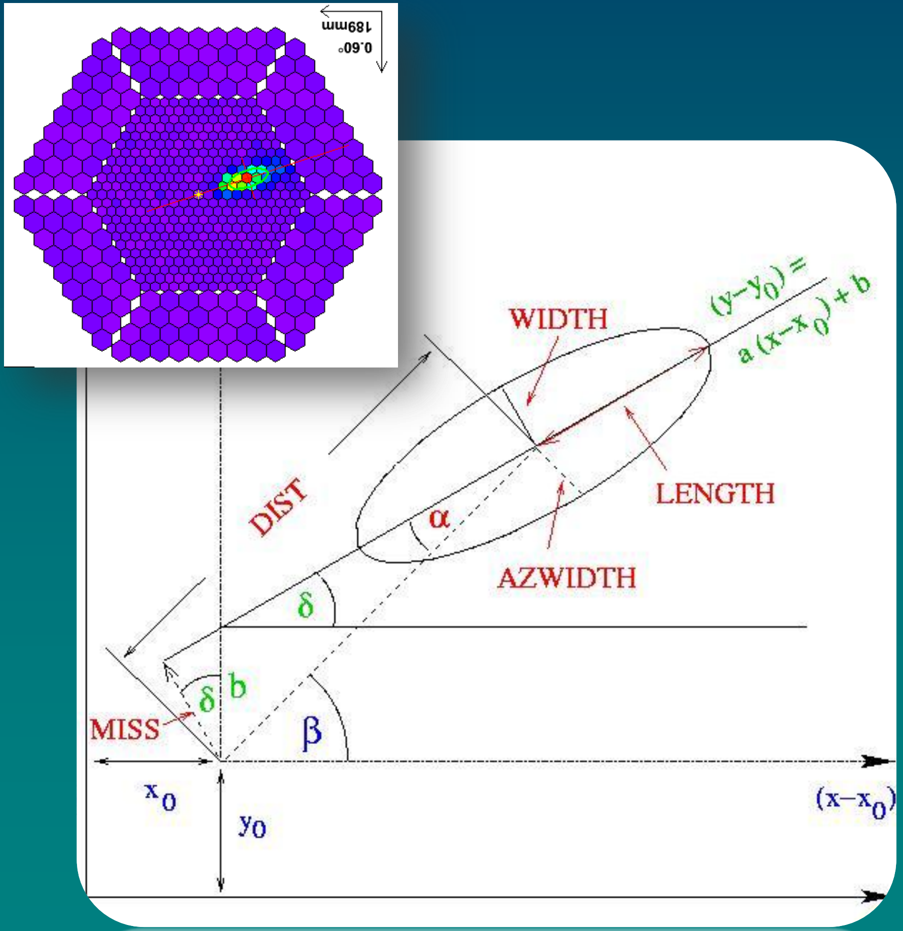
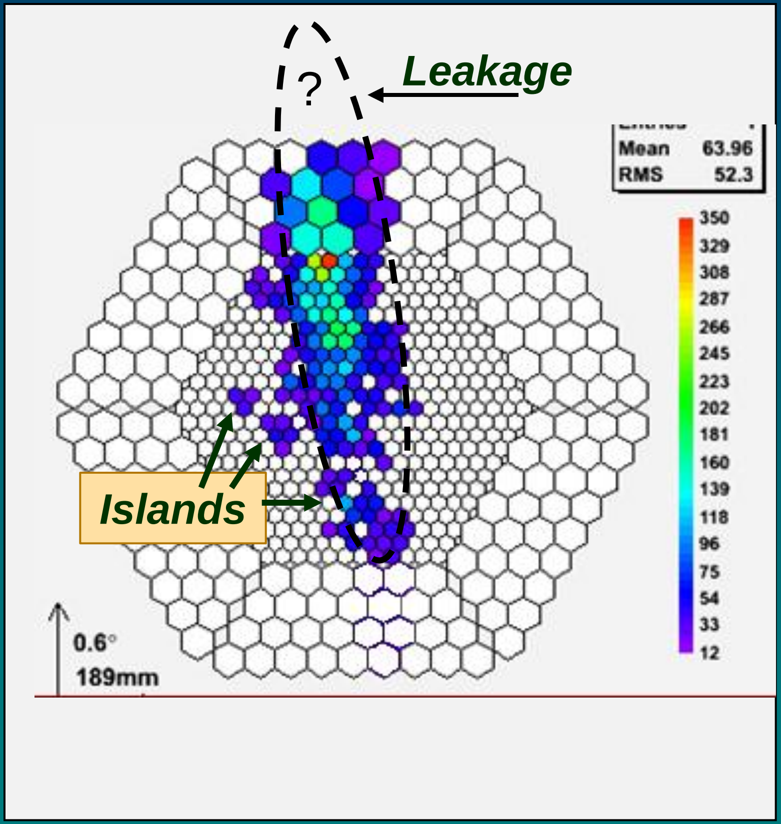


Image quality parameters

- **Number of island**
  - Number of separated groups of pixel
  - Can characterize the quality of the cleaning
- **Leakage**
  - Fraction of signal in the last pixel ring of the camera.
  - Characterize how the image leaks outside of the camera
- **Number of pixels**
  - Number of core pixels
  - Number of inner pixels



Source dependent parameters

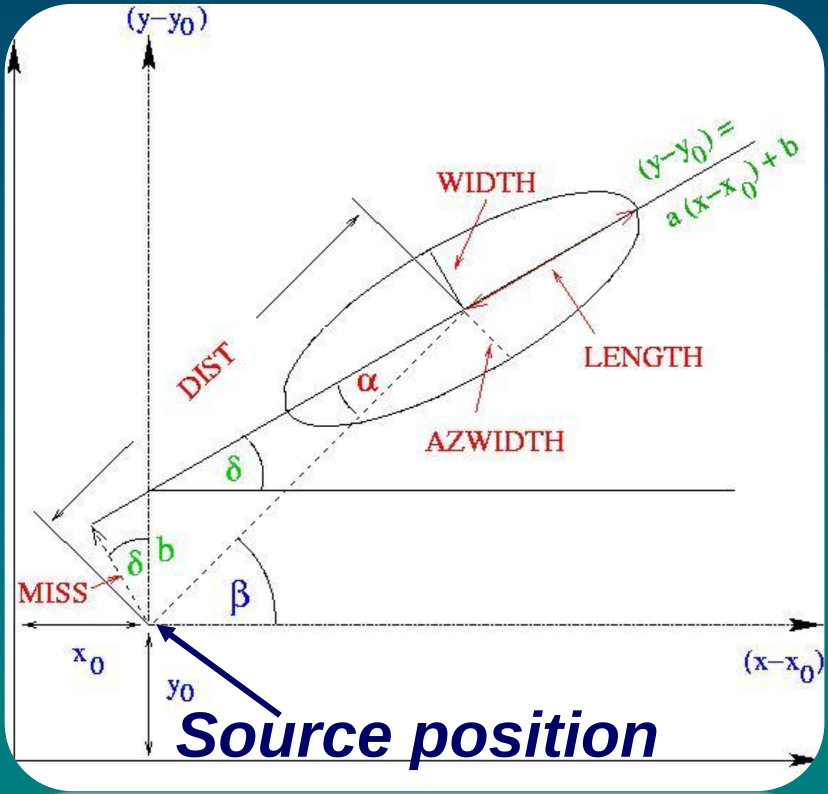
*Mainly used only for **single telescope** analysis*

- **ALPHA:**
  Angle between the main axis and the centroid-source line.

- **DIST (DISP):**
  Distance between the centroid and source position

- **MISS**
  Distance between the main axis and the source position

- **Azimuthal-Width:**
  Image width relative to the axis source-centroid



Extra Hillas parameters

- **Concentration (x):**
  - Fraction of the signal in x largest pixels
- **Asymmetry:**
  - Distance between centroid and highest pixel
  - 3rd moments of the signal distribution
- **Hillas parameters of the main island:**
- **And many others…**

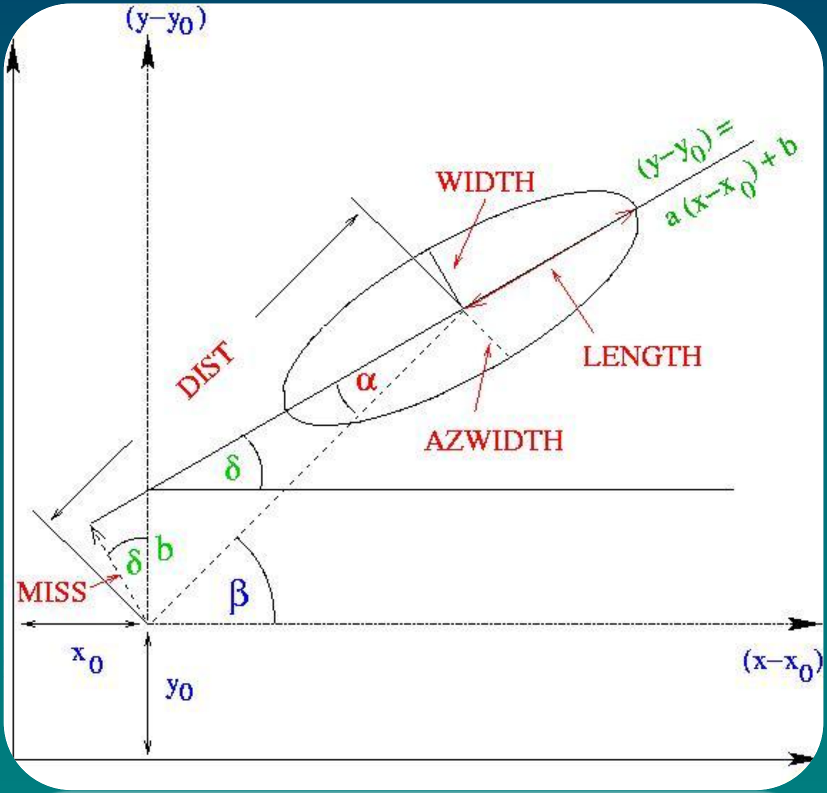
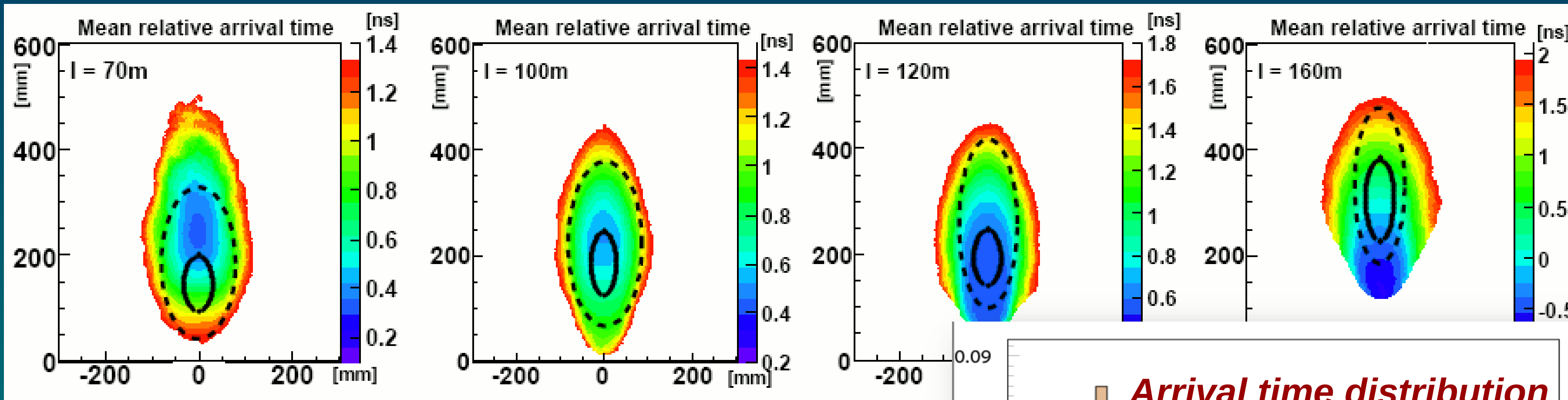
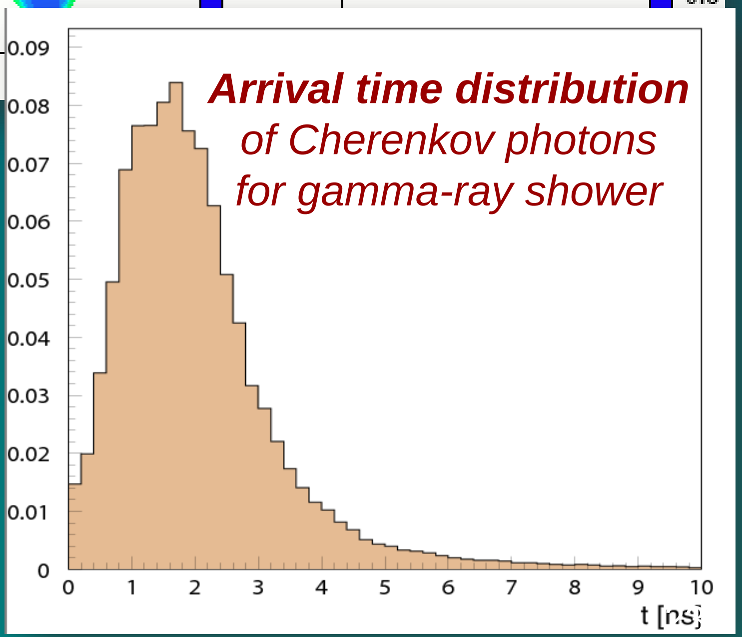


Image cleaning: Timing information

To decrease the cleaning levels, can additionally use the arrival time of photons in the camera





<u>For each Pixel we can get:</u>

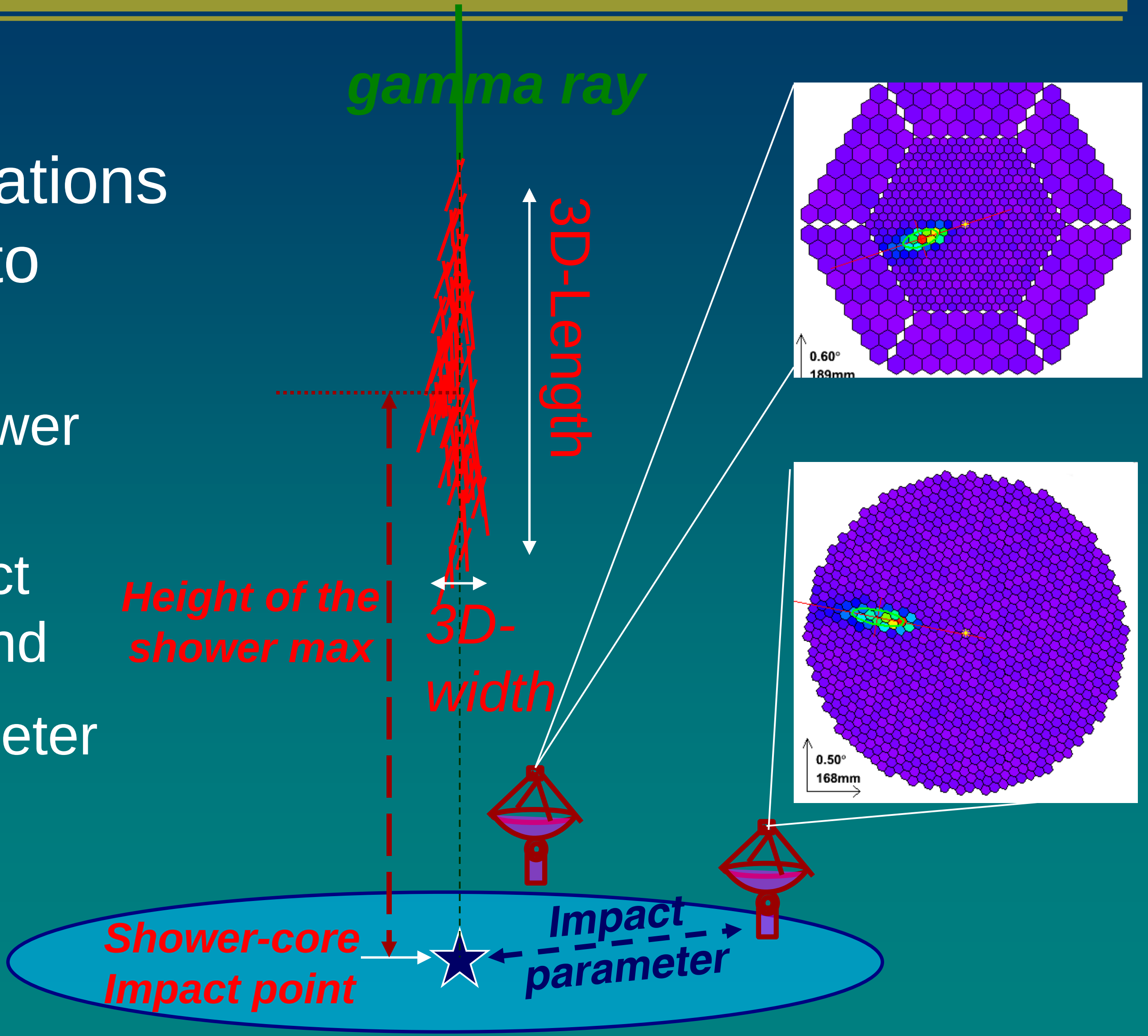
- pulse time
- pulse width

<u>Image information</u>:

- RMS of pixel time
- Time grad along main axis

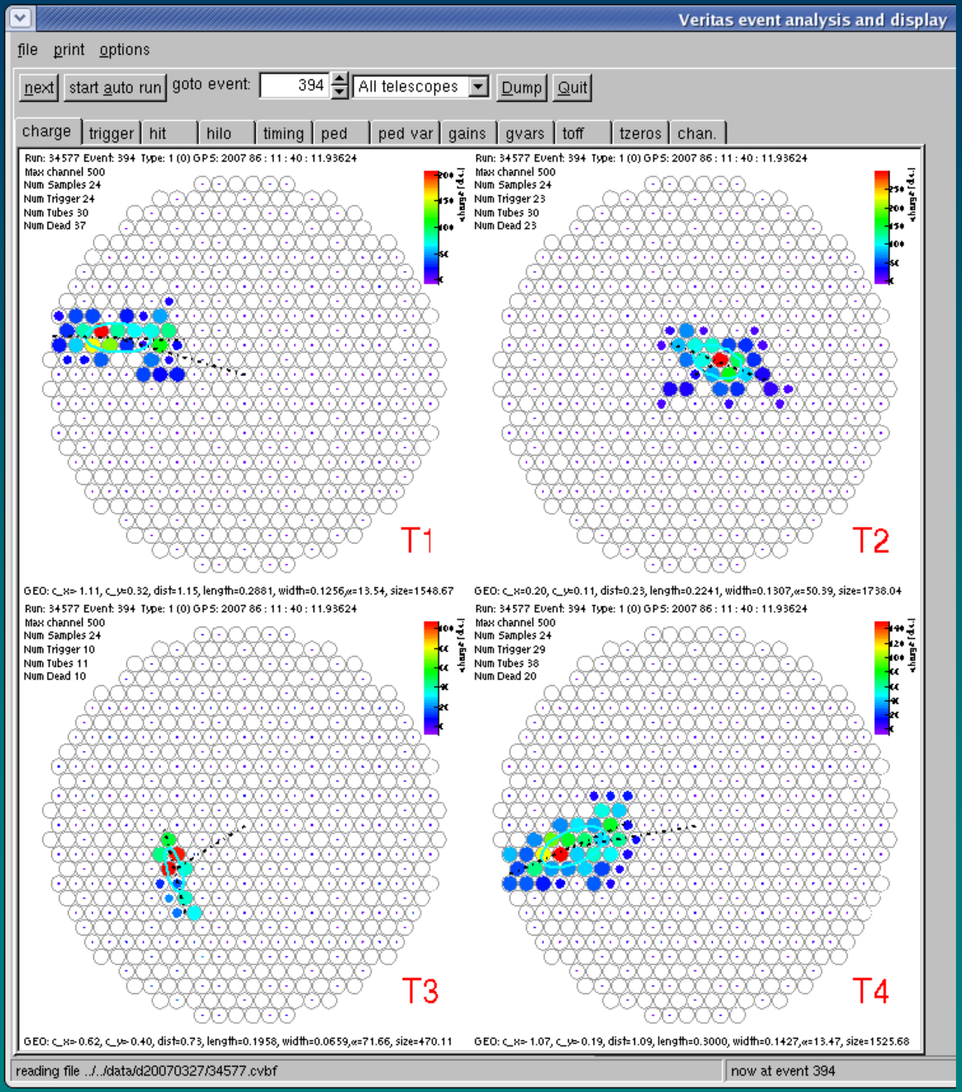
Stereo observations: 3D param.

- Stereo observations allows allows to reconstruct:
  - Height of shower maximum
  - Shower impact point on ground
  - Impact parameter



Multi-telescope parameters

- **Hillas parameters**
  - Mean Scale Width
  - Mean Scale Length
  - etc.
- **Event quality**
  - No. of triggering tel.
  - No. of clean images.
- **Time parameters**
  - time tel trigger RMS



Characterization of the event

Characterization of the event

Once we have obtained the shower image, the next step is to obtain the characteristics of the primary particle which originated the shower

Primary Direction:

- DISP method (1 telescope)

- Stereoscopic reconstruction (2 telescopes)

- 3D model analysis (n telescopes)

Primary Energy:

- Size vs Impact parameter model (1 telescope)

- Multi-parameters table or Random Forest (1 telescope)

- 3D model (n telescopes)

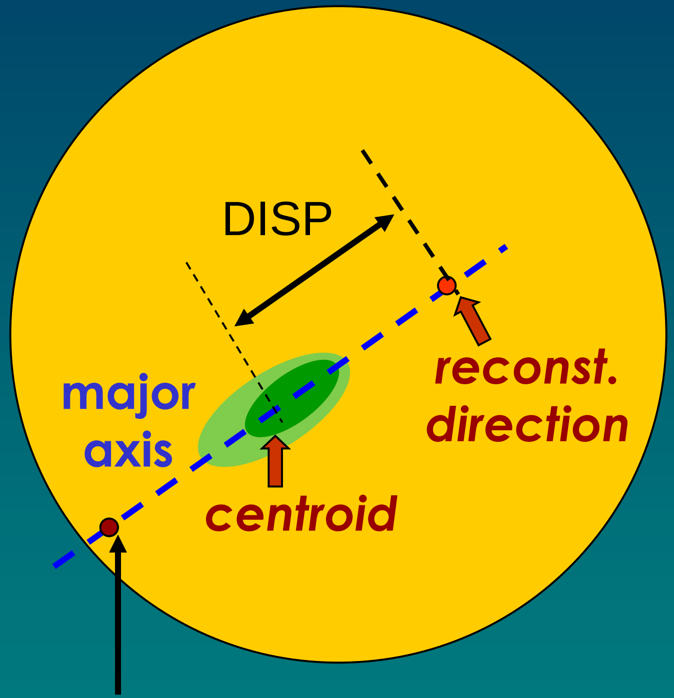
Background rejection:

- Cuts on the image and shower parameters

- Classification using a Random Forest

Reconstruction of the incoming direction

DISP method: Developed for single telescope data



Possible confusion with symmetric direction
Image asymmetry and time gradient help the distinction

DISP can be determined with:

- A parameterization:

$$DISP = A(SIZE) + B(SIZE) \cdot \frac{WIDTH}{LENGTH + \eta(SIZE) \cdot LEAKAGE2}$$

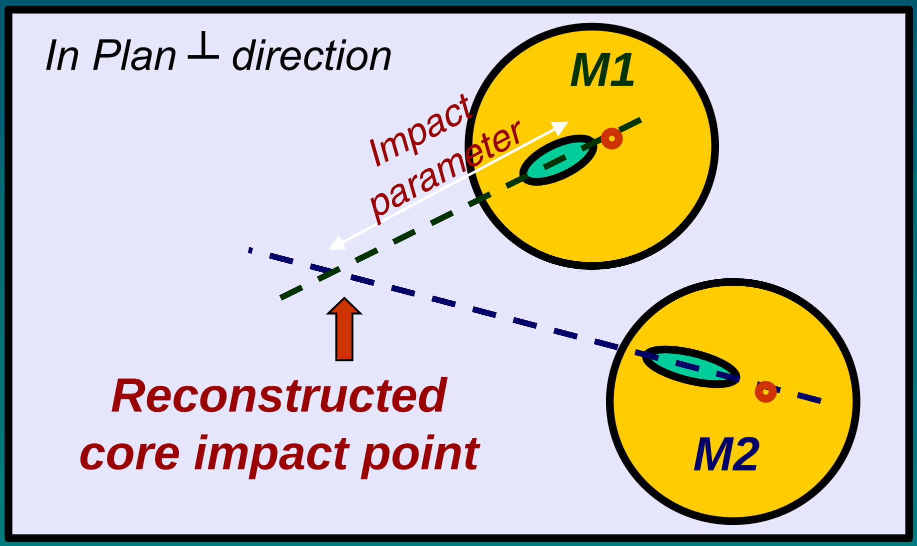
- Optimized decision trees
(Random Forest)

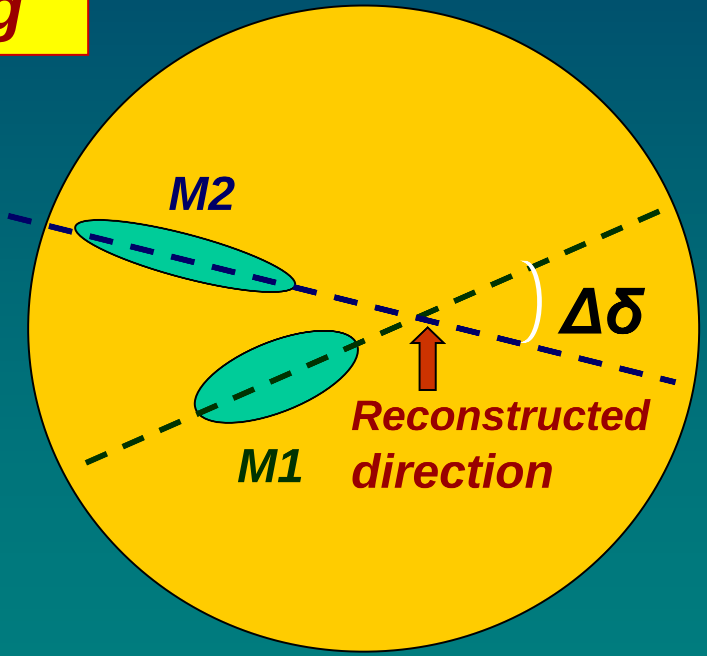
All methods are based on Monte Carlo Simulation

Reconstruction of the incoming direction

Geometrical reconstruction: for more than 1 telescope

Efficient for $\delta \geq 30$ deg





Mont Carlo independent

Reconstruction of the incoming direction

Final reconstructed direction

Input:

- One direction per telescope with DISP method
- One direction per telescope pair by stereoscopy

Waited average according
- ***Image quality***
- ***Size***
- ***Angle between image axes***

Output:

- The final primary direction
- Compatibility between the different results

Energy reconstruction

Basic fact: Energy ~ Image size

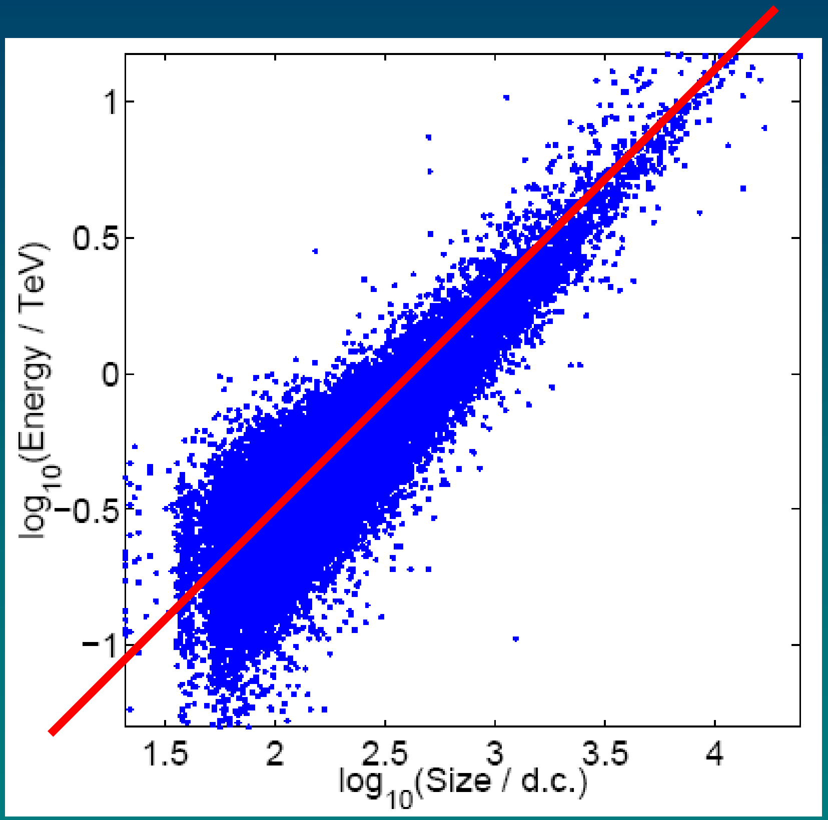
Methods:

- A parameterization:

Energy = f(size, impact, zenith,…)

- Look-up tables
- Optimized decision trees

(Random Forest)

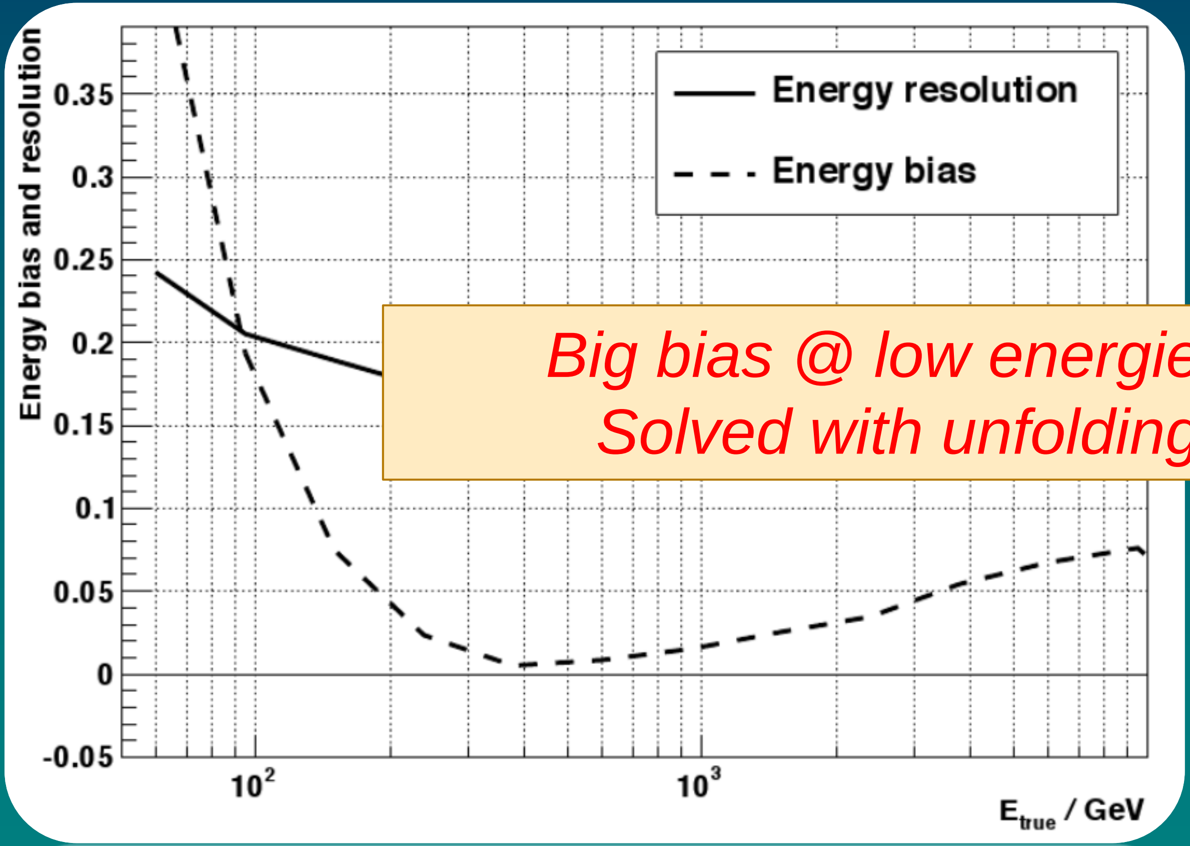


All methods are based on Monte Carlo Simulation

Energy reconstruction

Energy resolution:

20% at 100 GeV, down to 15% around 1 TeV



Big bias @ low energies.
Solved with unfolding

Gamma/hadron separation

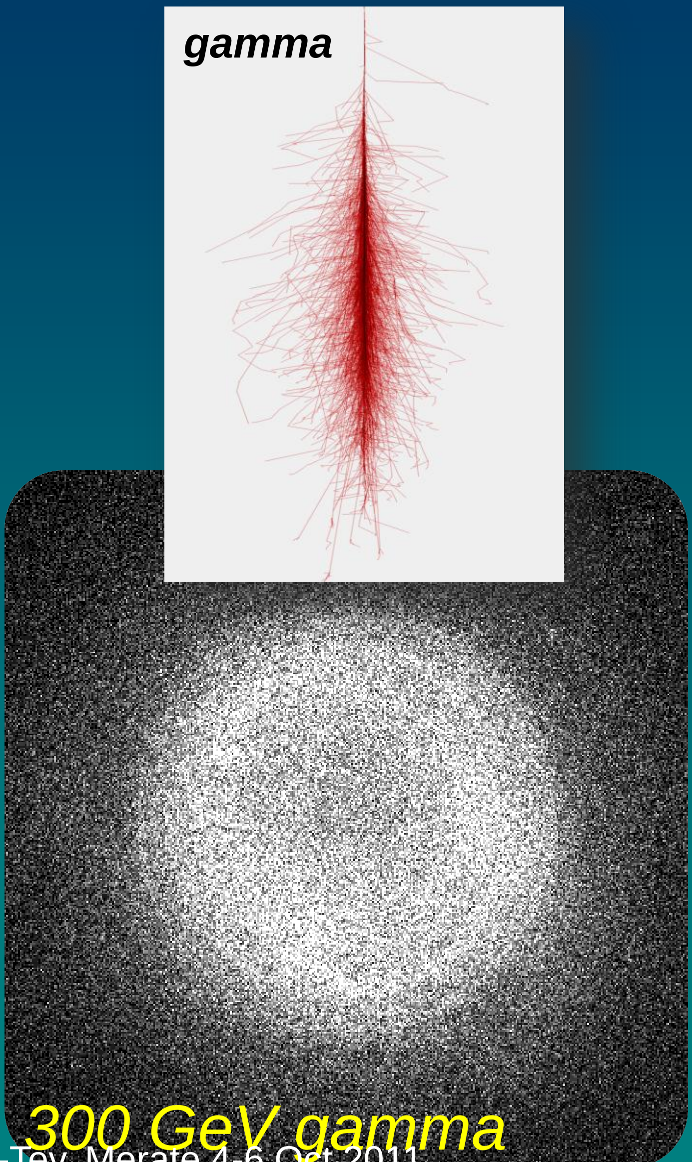
Cosmic-ray background

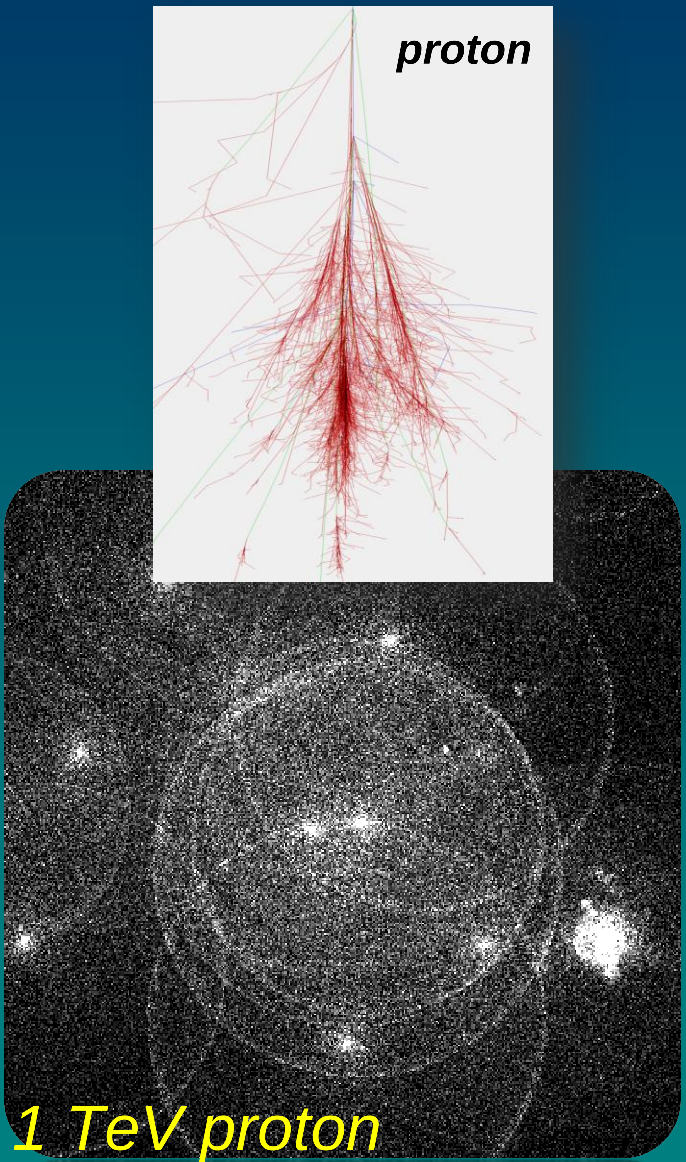
- Only air showers produce so rapid light flash But not only gamma-rays produce air showers !

Cosmic rays are composed of:

- **Protons** **(main background)**
- Heavy hadrons (Z>2) (easily rejected)
- Electrons (problem at low energy)
- Secondary muons (rejected by coincidence trigger)
- diffuse gamma-rays (No way !)
- neutrinos and other WIMPS (No problem)

Gamma/hadron separation

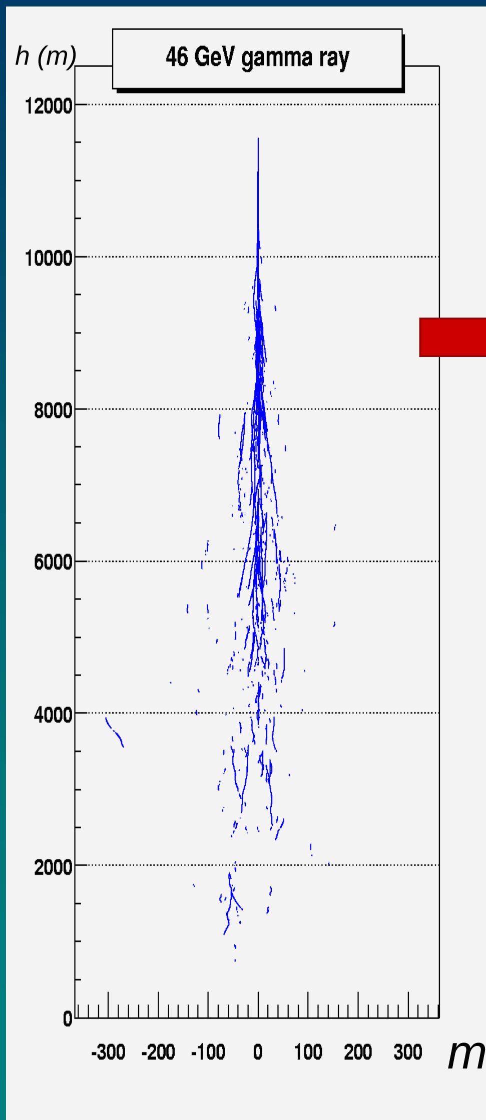




Gamma/hadron separation

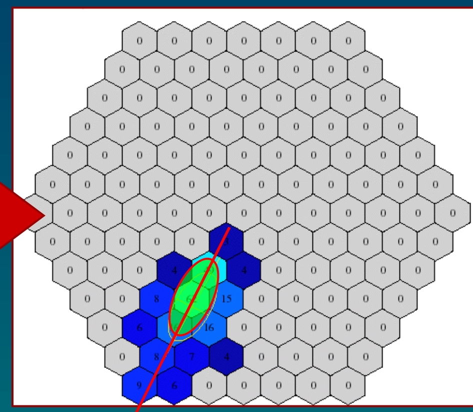
Different kind of primary particles produce different kind of images in the camera

Gamma/hadron separation



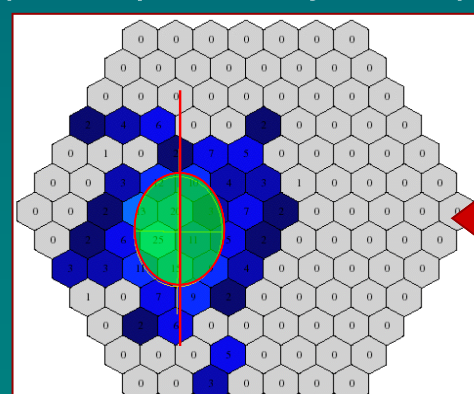
Gamma shower

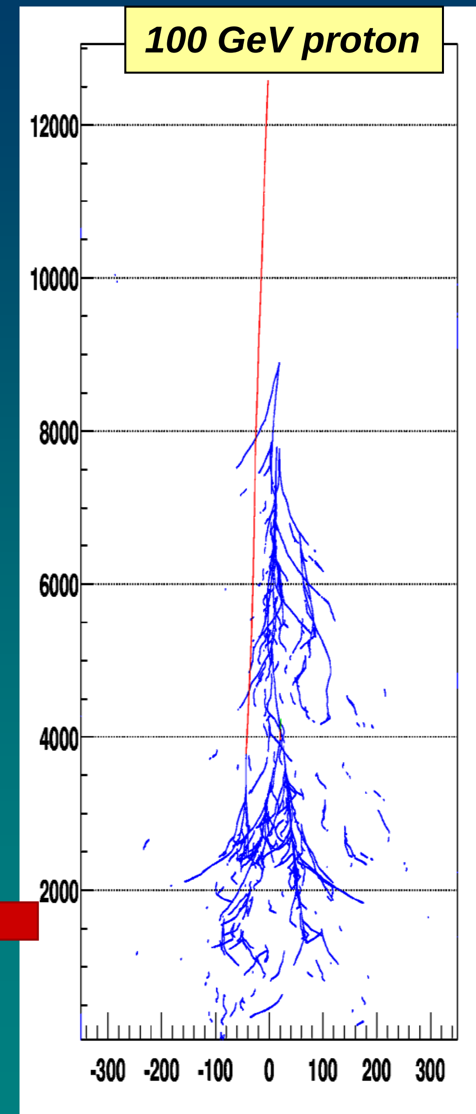
(narrow, points to source)



Proton shower

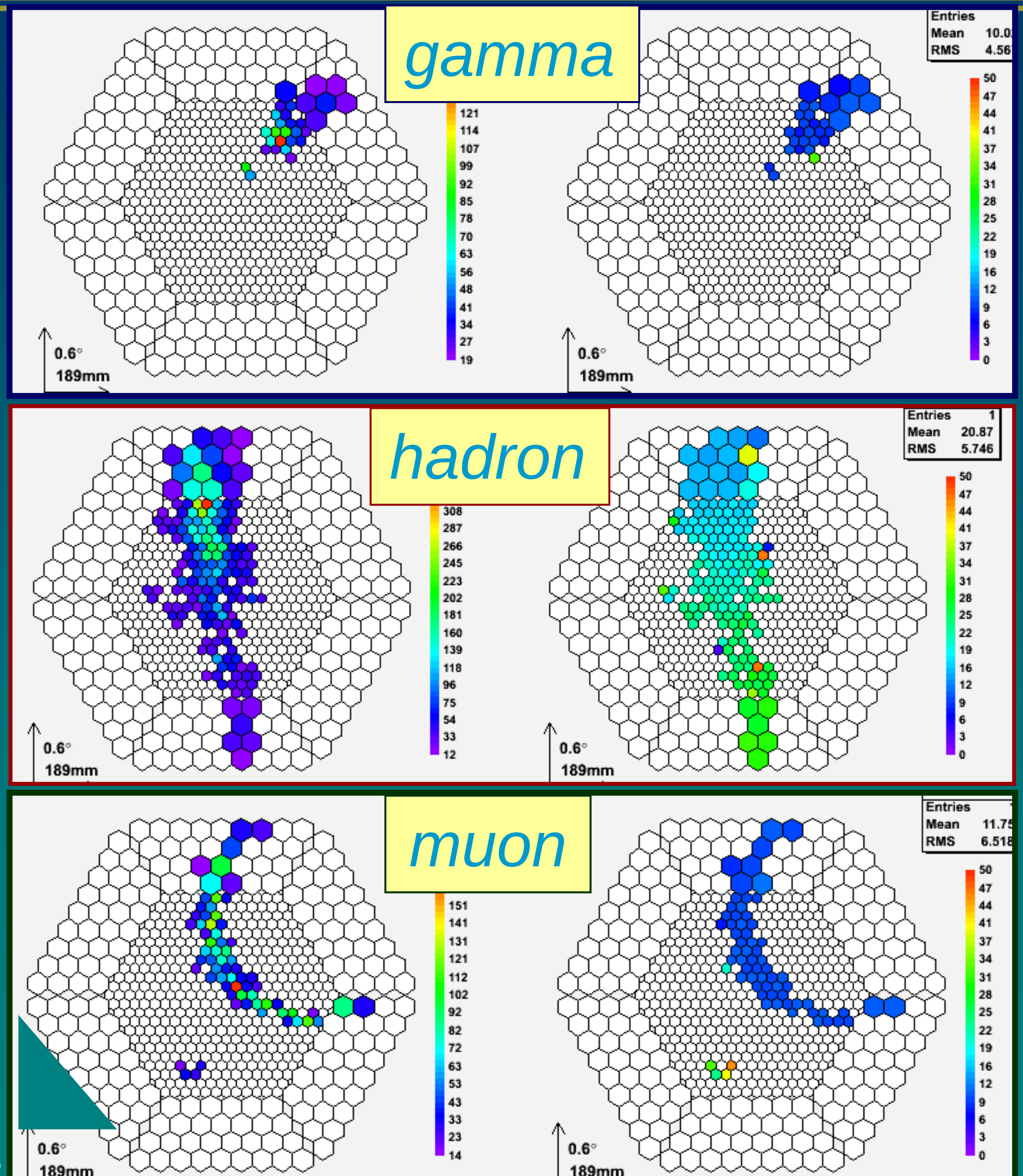
(wide, points anywhere)





Gamma/hadron separation

Signal



Timing

Gamma/hadron separation

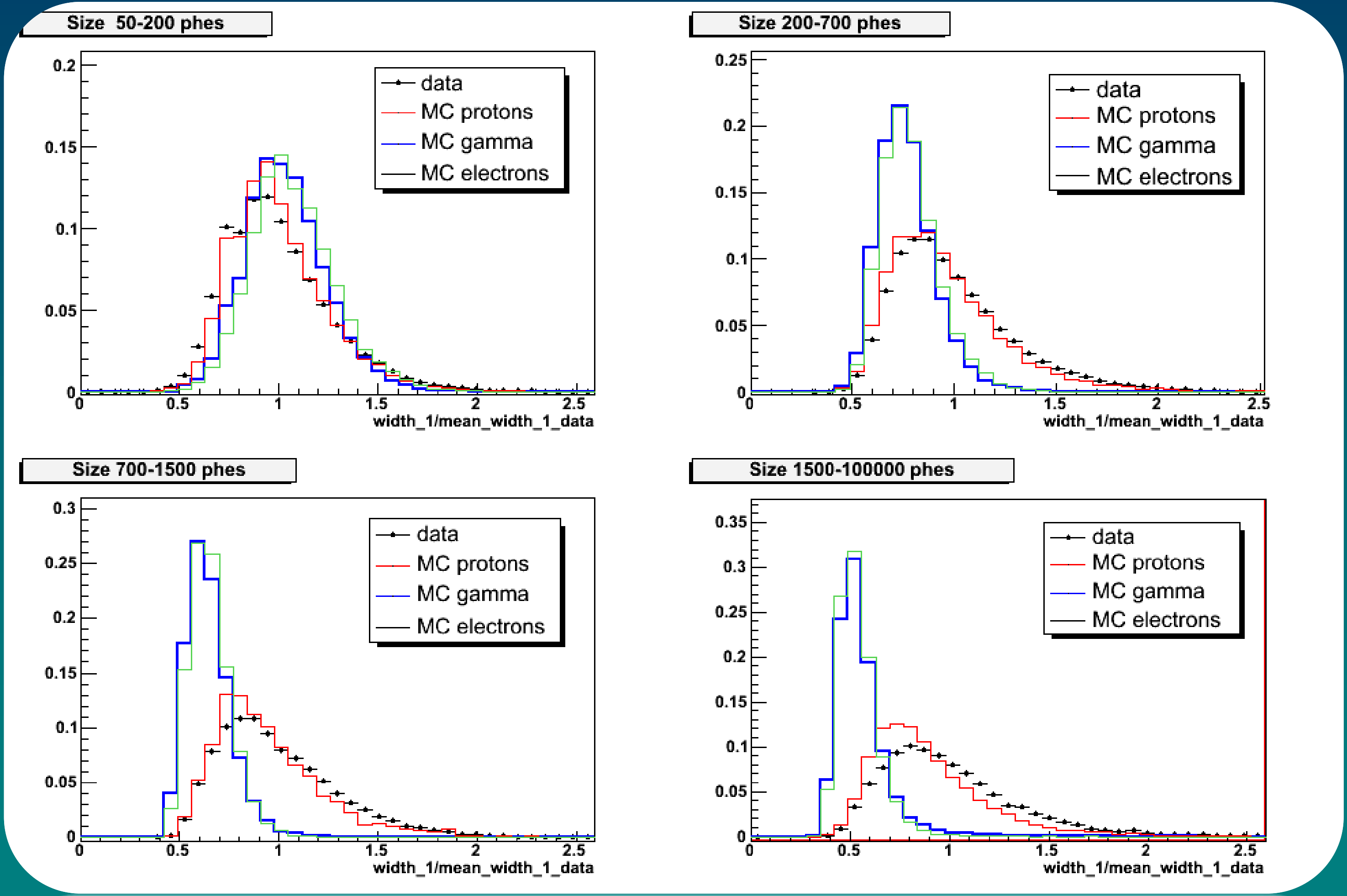
Different kind of primary particles produce different kind of images in the camera

↓

Different distributions of Hillas parameters

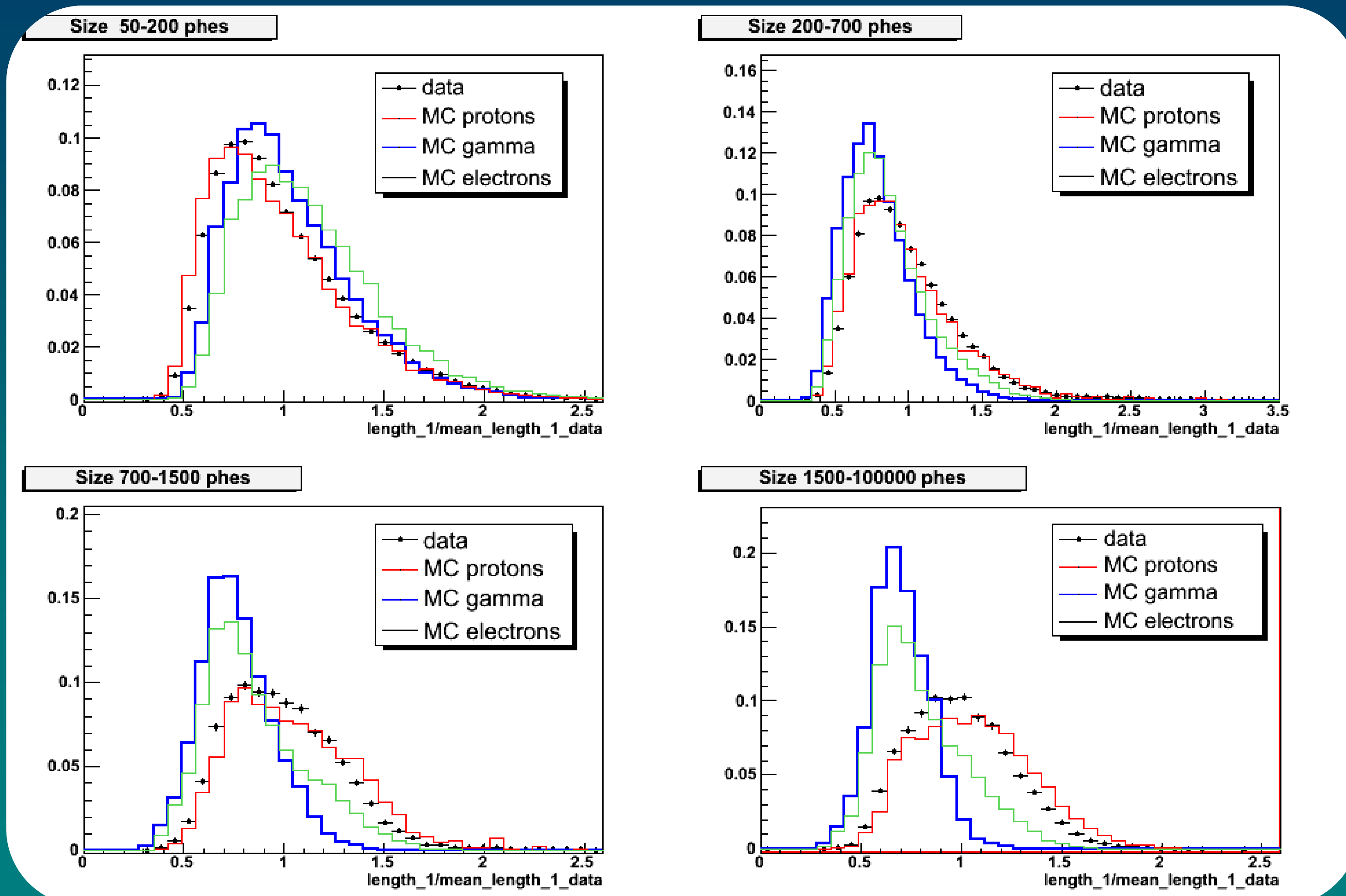
Gamma/hadron separation

- Width



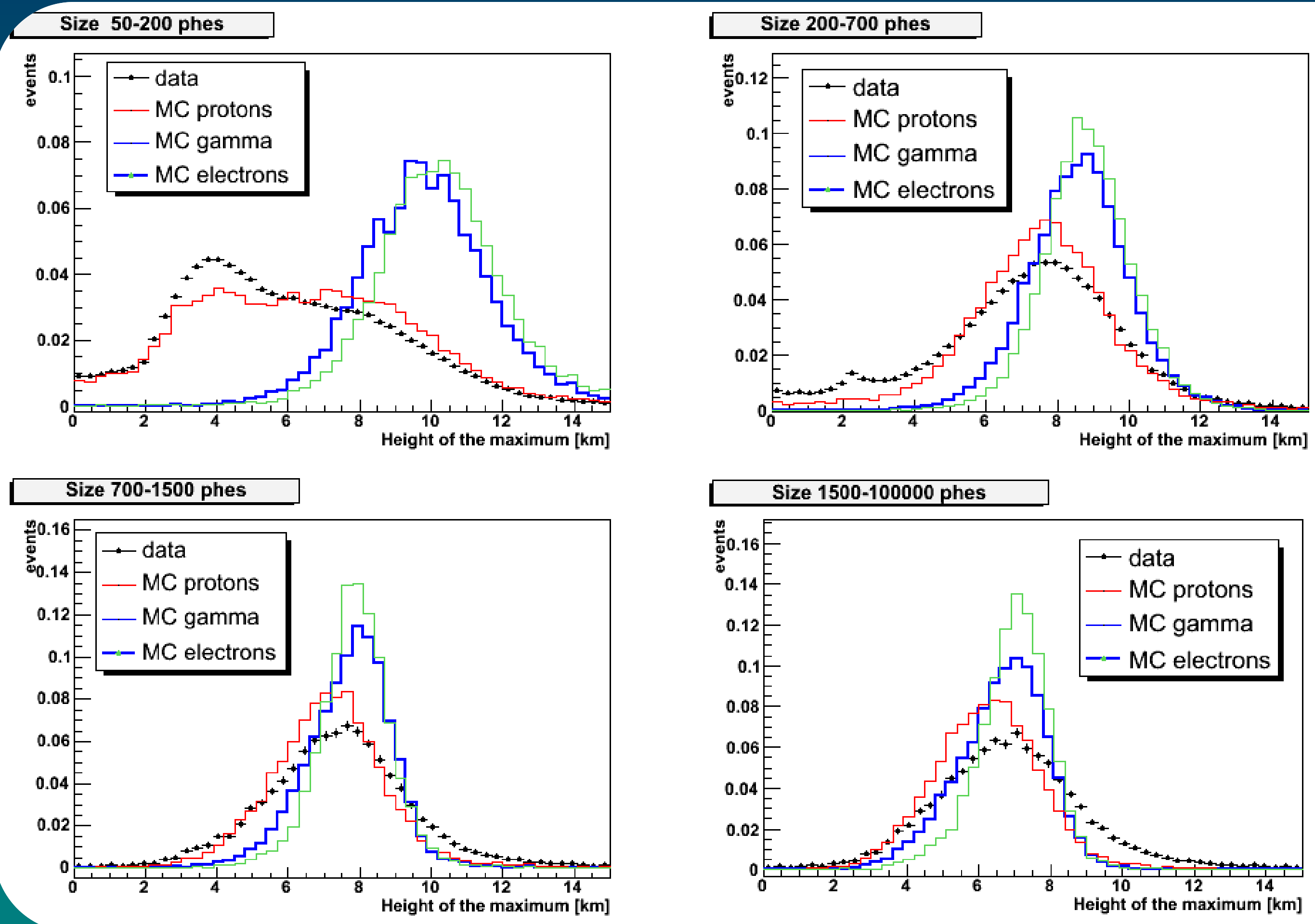
Gamma/hadron separation

- Length



Gamma/hadron separation

- Height of Shower maximum

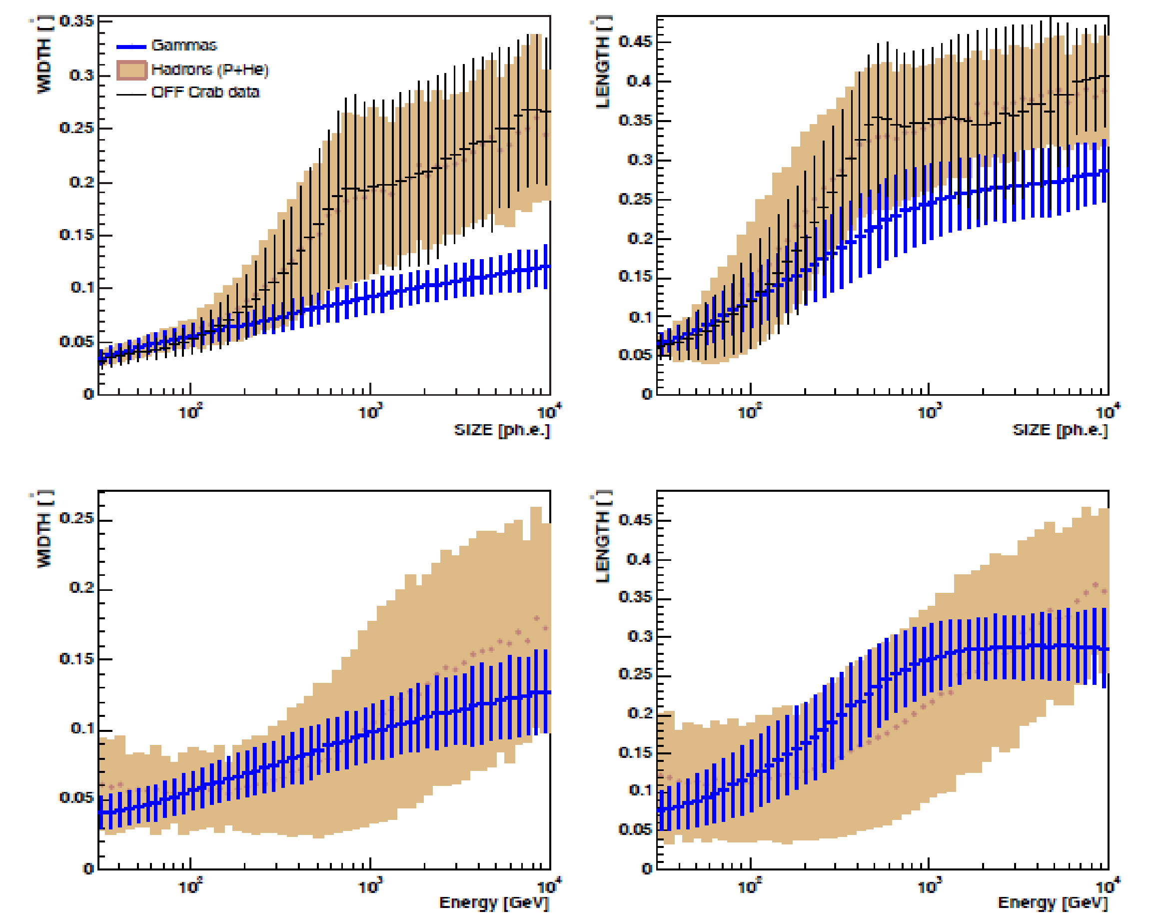


Gamma/hadron separation

Methods:

- **Super Cuts:**

Cuts on image or/and shower parameters



Parameters change with Energy --> so the cuts

Gamma/hadron separation

Methods:

- **Super Cuts:**

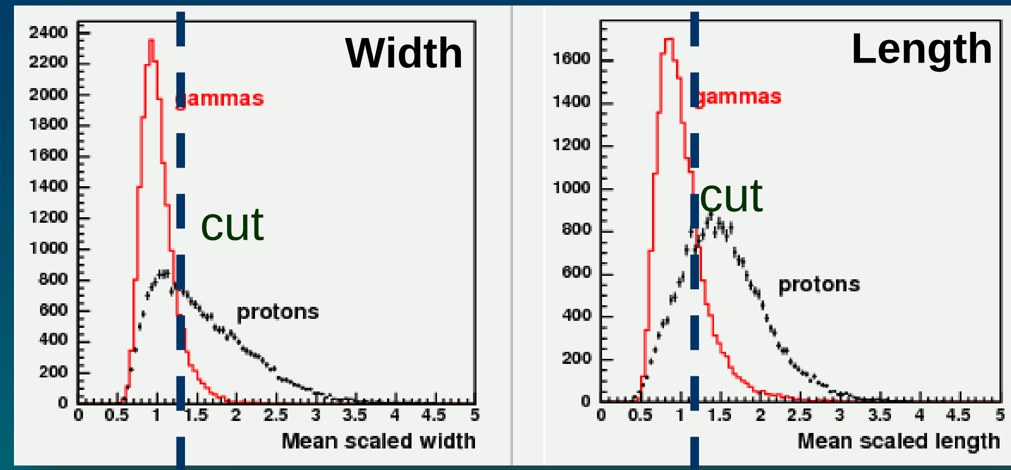
  Cuts on image or/and shower parameters

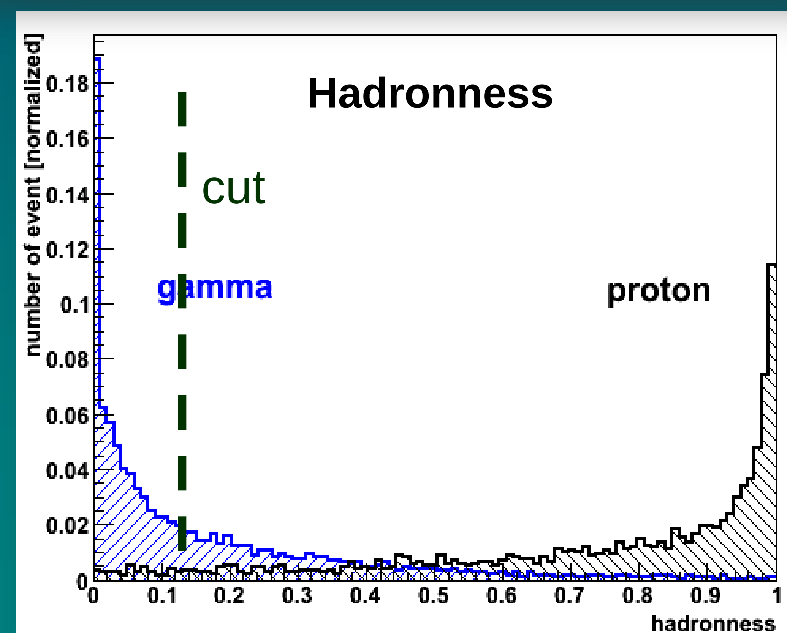
- **Random Forest:**

  Optimized decision trees

- **Other ?**

  (Likelihood fit goodness of an analytic model)





Random Forests

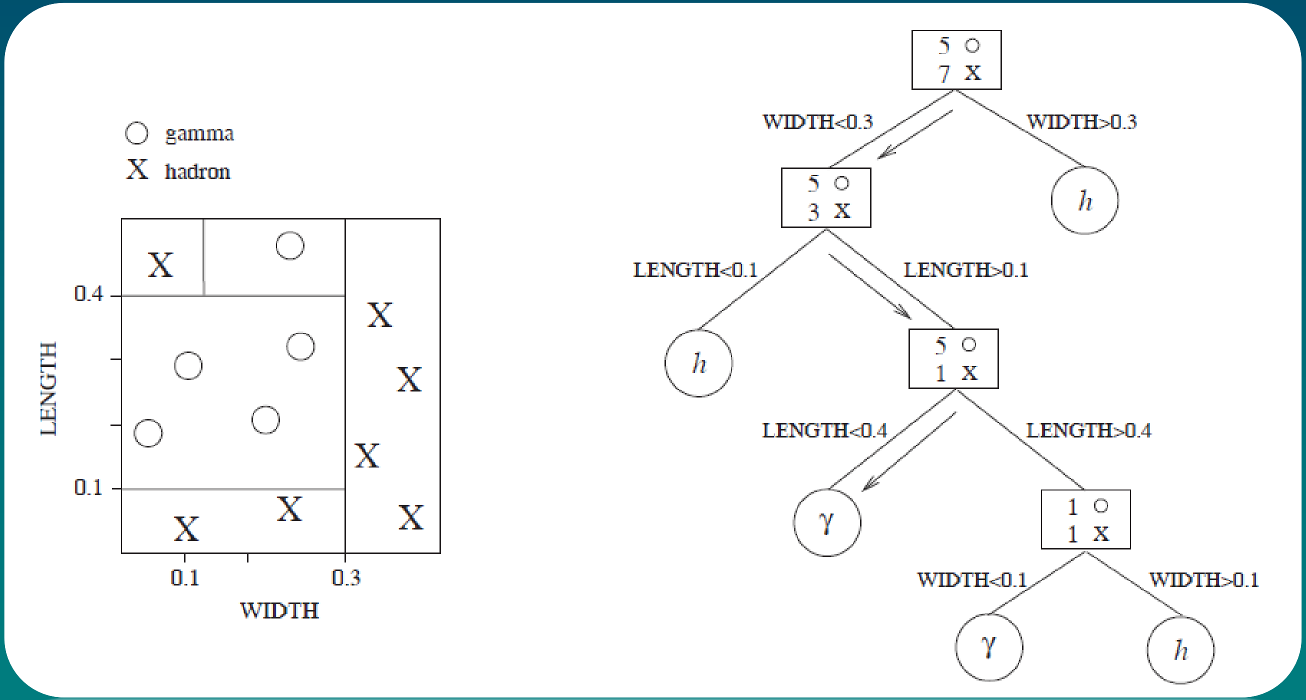
- A random forest is a numerical tool
- Ingredients:
  - MC Train samples of both species (Gammas & hadrons)
  - Parameters to be used
  - Statistical settings: #trees, #trials, final nodesize
- Advantages:
  - Fast calculation (compared to other classification methods)
  - Very good separation
  - Offers energy dependent cuts

The method implemented by MAGIC

Random Forests

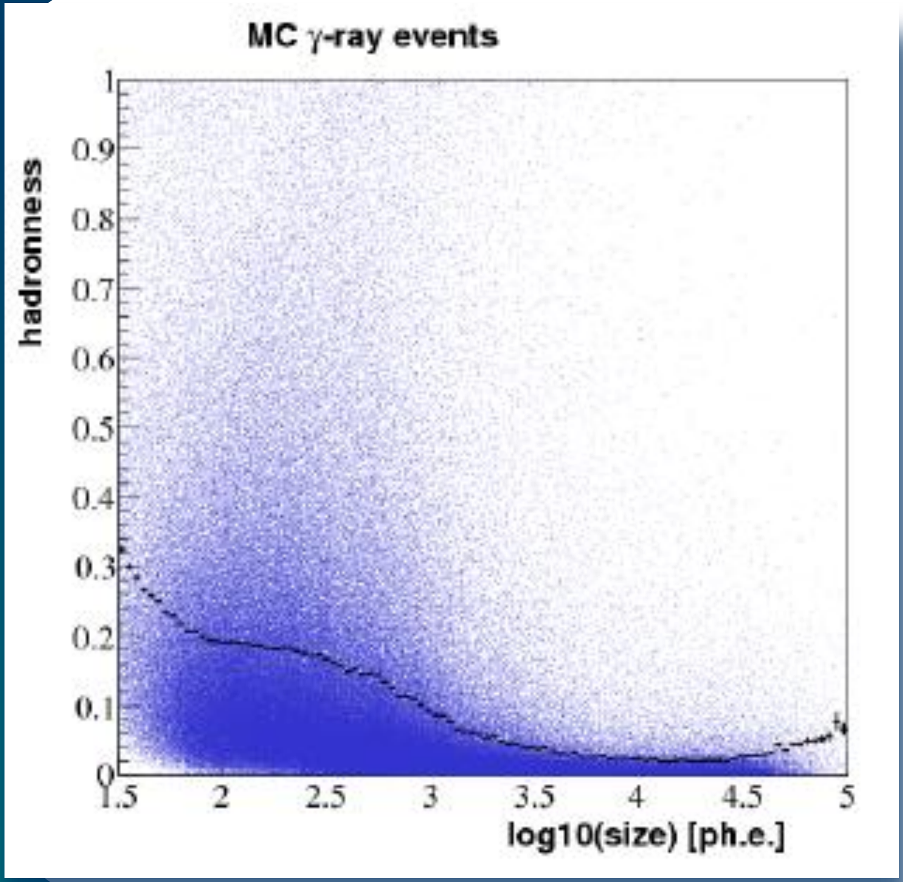
Who it works: *The growing of a tree*

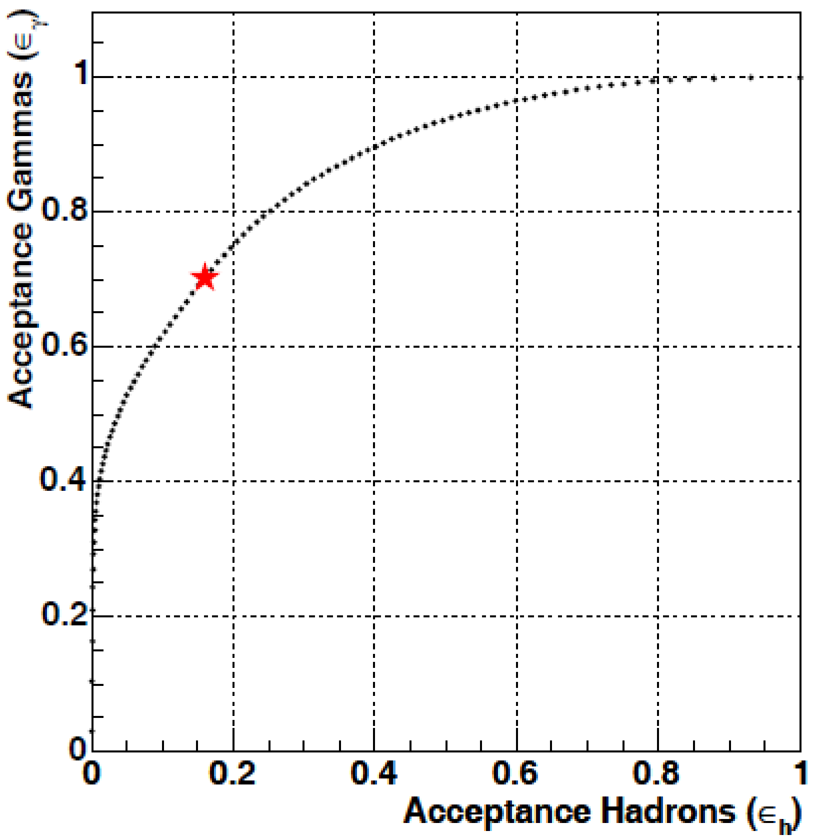
- Space parameter divided into hypercubes
- Each division done choosing randomly an Image parameter



- Algorithm ends when in each final node there is only one kind of event (gamma or hadron)

Random Forests





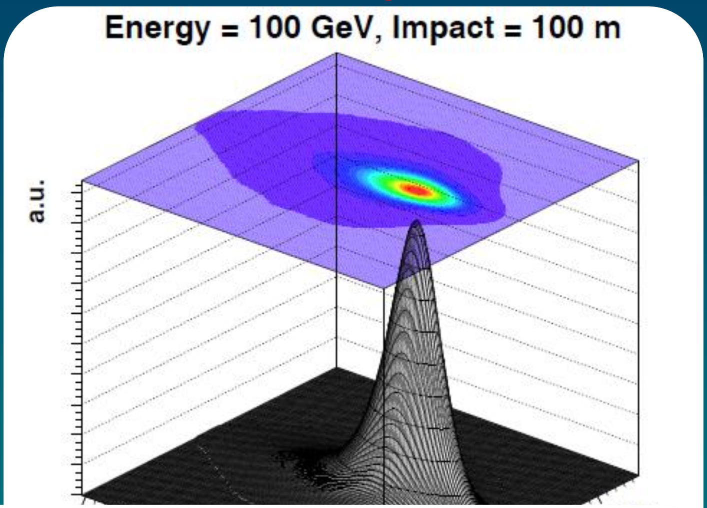
Finally, one applies a cut in the HADRONNESS.
Cut depends on the desired gamma purity of the sample and changes with energy

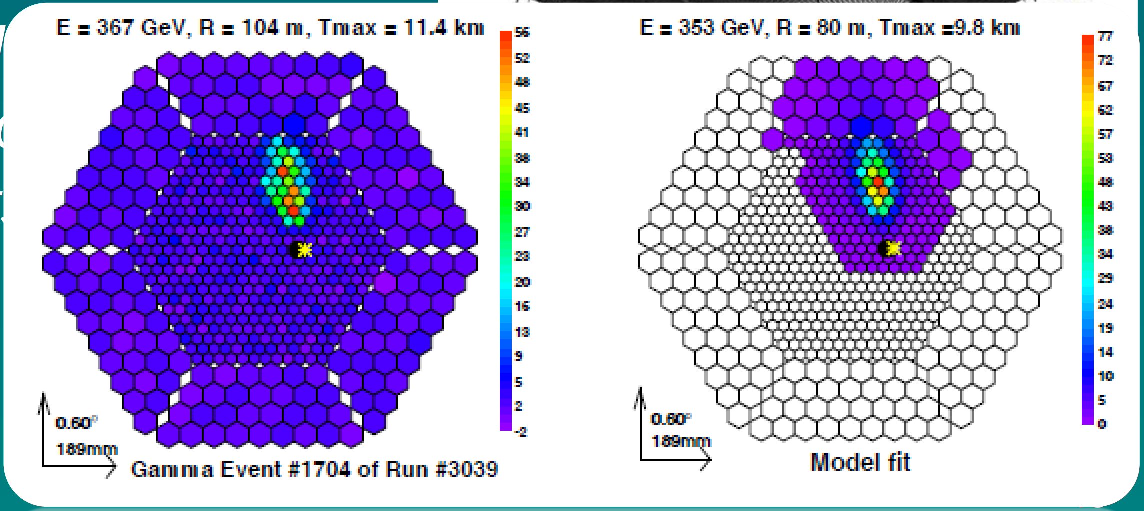
Model analysis: A Global reconstruction method

An alternative to the use of image parameterization

- *Analytic model (based on MC) gives the expected signal in each pixels as a function of E, Direction & Impact*
- *A fit of the MC templates on the real data reconstructs at same time the E, direction, and nature (gamma/hadron)*
- *This method developed then by HESS is time c provides the best result telescope arrays).*

MC template





Last word: Systematic Effects

Every step has its own uncertainties which propagates up to the final physical results

- Calibration (absolute PMT QE, mirror aging, …)
- MC Simulations (atmospheric model, trigger, …)
- Background estimation (camera inhomogeneity, …)
- Whether condition (Calima, high clouds,…)
- Night sky light (Bright stars, Moon light, …)
- Telescopes condition (dead pixels, misspointing, …)
- Analyzer choices (cut optimizations, binning, …)

Generally, IACTs claim 20% systematics

That’s all.
Thanks for your attention